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T. E. RUBY

THE MEASUREMENT OF THE HYSTERESIS LOSS DIRECTLY

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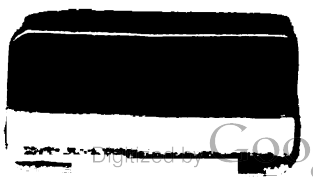

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THE MEASUREMENT OF THE HYSTERESIS LOSS DIRECTLY

by

TAYLOR EARLY RUBY

A Thesis Submitted for the Degree of

BACHELOR OF ARTS

UNIVERSITY OF WISCONSIN

1910

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THE MEASUREMENT OF THE HYSTERESIS LOSS DIRECTLY

INTRODUCTION

The commercial importance attached to the magnetic properties of iron and steel in the construction of electrical machinery makes necessary an accurate and quick method for testing the qualities of all iron used. The most important property, and one which is common to all samples, is its tendency to persist in any magnetic state in which it has been previously placed. Thus, when a sample has been subjected to a magnetizing field of a certain strength, on the withdrawal of the field, much of the magnetism remains. This residual magnetism is the result of the reluctance, offered by the metal, to change its magnetic state. The necessity for measuring this hysteresis effect has led to the developement of several methods of measurements of which the most important are those which make use of the wattmeter, the special hysteresis meters, the magnetometer, and the ballistic galvanometer.

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The wattmeter method, while having the advantage of rapidity and ease of calculation, is subject to errors which renders the results only approximate. Of these errors the most important is due to the fact that it necessitates the measurement of eddy current loss along with the hysteresis loss, the elimination of which is rendered difficult on account of the uncertainty in the frequency and wave shape of the voltage applied to the magnetizing coil. The special hysteresis methods are subject to error in the measurement of the maximum magnetic flux density and its distribution in the specimen under test. The last two methods are very accurate but they necessarily involve taking many readings and plotting the results to scale before the hysteresis loss can be determined. The time required for the determination of the loss by these methods and the inaccuracy of the former methods led Rice and McCollum[1] of the University of Kansas to develop the ballistic electrodynamometer, an instrument which is as quick as the wattmeter and yet free from the defects inherent in the more rapid methods. It is my purpose in this thesis to construct an instrument and test the theory as given by the above authors.

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[1]Physical Review, XXIX, 132, 1909.

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THE BALLISTIC ELECTRODYNAMOMETER:- This instrument was constructed with two fixed field coils, with a mean diameter of 4 5/8 inches and having 250 turns of number 12 copper wire. They were placed four and one-half inches apart and between these was suspended, by means of a phosphor-bronze fibre, a coil of 180 ohms resistance. The reversing switch S was constructed so as to close the circuit on one side before opening it on the other, thus enabling the dynamometer to measure the entire loss through a half cycle. All iron was carefully avoided in the construction of the instrument. This was especially necessary for the movable coil. The iron impurities, even in the copper wire, in some specimens need to be guarded against for the iron becomes magnetized to some extent, by the magnetizing field, thereby lessening the accuracy of the instrument.

THEORY OF THE METHOD.

In order to measure the hysteresis loss per cycle the instrument was arranged as shown in Fig. 1. The ring Fe was magnetized to any desired amount by adjusting the rheostat Rh; the current passing in series through the ammeter A, the reversing switch S, the magnetizing coil C_1, the field

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The Arrangement of the Apparatus and View of the Instrument Used.

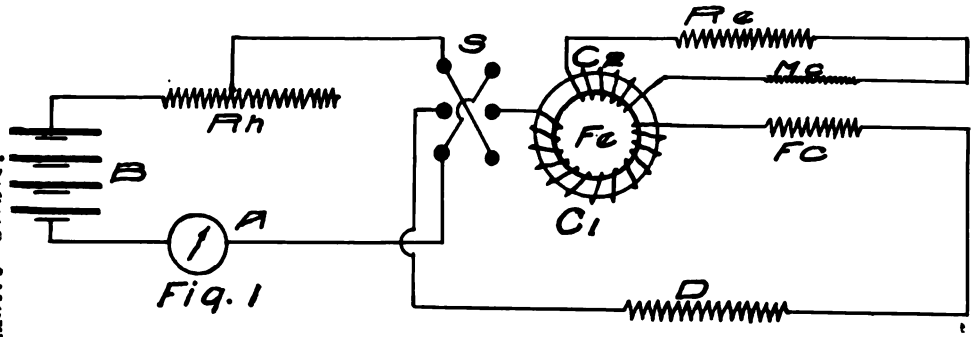
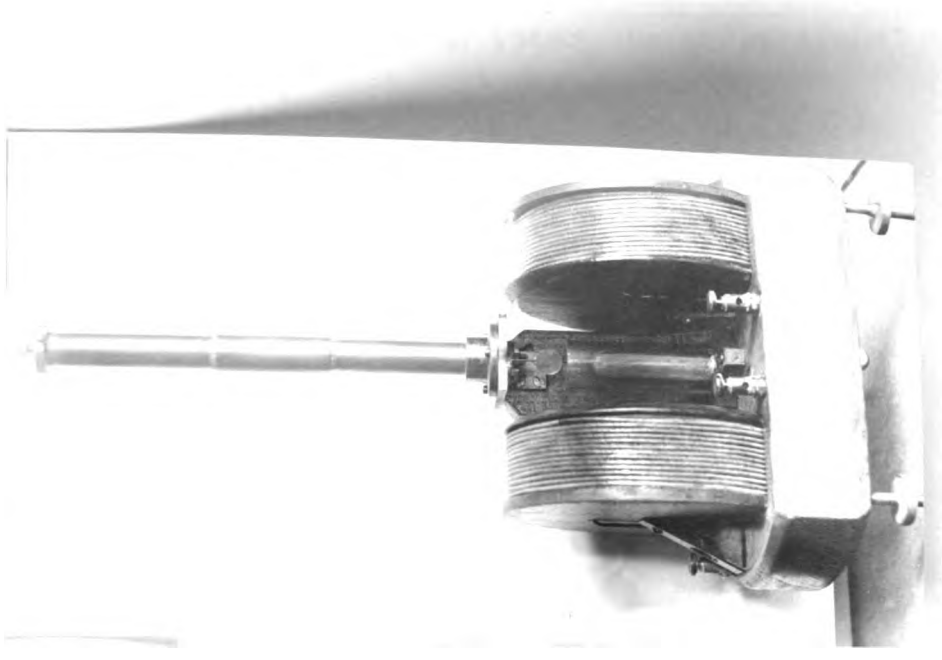


Fig. 1



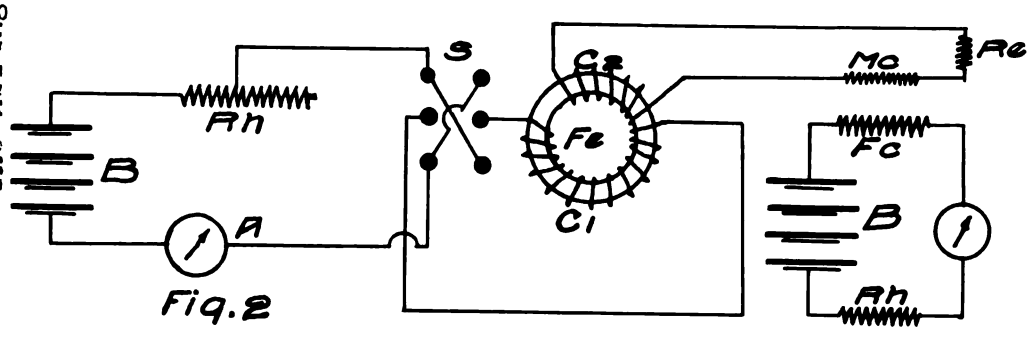


Fig. 2

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coils Fc of the dynamometer and the choke coil D. The secondary or test coil circuit was connected in series with the movable coil of the dynamometer. The reversal of the switch S caused a deflection of the movable coil because of the current induced in the secondary circuit. W, the energy loss per half?cycle corresponding to the magnetizing current I, as will be shown later, is proportional to the ballistic throw: i.e.

$$W = K_1 \theta \qquad (1)$$

where θ is the observed deflection, and K_1 a calibration constant defined by the equation

$$K_1 = 2n_1 r_2 CVI' \theta / n_2 \theta'$$

where n_1 = the number of turns on primary of ring.

n_2 = the number of turns on secondary of ring.

C = capacity of condenser.

V = difference of potential to which condenser was charged.

I' = the current in the ring and field coils.

θ' = the calibration deflection.

r_2 = the resistance in test coil circuit.

θ = observed deflection on ring tested.

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The working equation, to be derived, is given by

$$W = 2\pi n_1 r_2 C V I' \theta / n_2 \theta' = K_1 \theta. \qquad (2)$$

The letters used for the mathematical proof of equation (2) are defined as follows:-

φ = total instantaneous flux in the iron ring.

e_1 = the instantaneous counter E.M.F. in the magnetizing coil.

e_2 = the instantaneous generated E.M.F. in the test coil.

i_1 = the instantaneous current in magnetizing coil.

i_2 = the instantaneous current in test coil.

K = the moment of inertia of the movable coil.

g = a constant of the dynamometer depending on its windings

b = the torsion constant of the suspension fibre.

θ = the instantaneous deflection of dynamometer.

ω = the instantaneous velocity of moving coil.

T = the instantaneous torque acting on the moving coil due to the currents i_1 and i_2.

P = the instantaneous power expended in the iron and test coil circuit.

W/2 = the total energy expended per half cycle in the iron and test coil circuit

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In the primary circuit,

$$P = e_1 i_1 = i_1 n_1 d\varphi/dt \text{ whence } i_1 = P/n_1 d\varphi/dt. \quad (3)$$

In the secondary circuit,

$$i_2 = e_2/r_2 = n_2 d\varphi/dt/r_2. \quad (4)$$

The torque acting on the movable coil of the dynamometer on a reversal of switch S is proportional to the primary current i_1 and to the induced secondary current i_2, or

$$T = g i_1 i_2. \quad (5)$$

The values of i_1 and i_2, from equation (3) and (4) substituted in above equation gives,

$$T = g P n_2 d\varphi/dt / r_2 n_1 d\varphi dt = g P n_2 / r_2 n_1. \quad (6)$$

Multiplying each side of the equation by dt we have

$$T dt = g n_2 P dt / r_2 n_1. \quad (7)$$

The angular acceleration $d\omega/dt$ imparted by the torque T

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to the moving coil of the dynamometer, considering that the entire discharge takes place before the coil has moved appreciably, is given by the equation

$$d\omega/dt = T/K \; ; \; \therefore T dt = K d\omega . \qquad (8)$$

Substituting the value of T·dt in equation (7) and integrating between limits we get

$$\int_{\omega=0}^{\omega=\omega_{max.}} K d\omega = g n_2/r_2 n_1 \int_{t=0}^{t=\infty} P dt . \qquad (9)$$

The first integral of equation (9) is the total angular momentum of the moving coil of the dynamometer at the instant when the secondary discharge has been completed; while the second integral of the equation represents the total energy W/2 expended in the iron ring and secondary circuit per half cycle. The value of these integrals, substituted in equation (9), and solved for $\omega_{max.}$ gives

$$\omega_{max.} = g n_2 W/2 K r_2 n_1 . \qquad (10)$$

The total kinetic energy of the movable coil at any instant is given by the equation, $W_1 = 1/2\ K\omega^2$, and its rate of

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change is

$$dW_1/dt = K\omega\, d\omega/dt. \qquad (11)$$

The total energy stored in the suspension fibre at any instant is $W_2 = 1/2\ b\theta^2$. The rate of change of this potential energy is

$$dW_2/dt = b\theta\, d\theta/dt. \qquad (12)$$

For an undamped instrument the rate of change of potential energy and kinetic energy are equal and opposite in sign. From equations (11) and (12) we obtain

$$K\omega\, d\omega/dt = -b\theta\, d\theta/dt \qquad (13)$$

and by multiplying each side by dt and integrating between limits, we have

$$K\int_{\omega=\max.}^{\omega=0} \omega\, d\omega = -b\int_{\theta=0}^{\theta=0} \theta\, d\theta \qquad (14)$$

which gives

$$\tfrac{1}{2} K\omega^2_{max.} = \tfrac{1}{2} b\theta^2. \qquad (15)$$

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This equation is true for damped instruments as well as undamped ones. Solving equation (14) for $\omega_{max.}$ we get

$$\omega_{max.} = \theta\sqrt{b/K}. \qquad (16)$$

Eliminating $\omega_{max.}$ from (10) and (16) we obtain

$$W = 2\sqrt{bK}\,K r_2 n_1 \theta / g n_2 . \qquad (17)$$

CALIBRATION OF THE DYNAMOMETER.

The unknown factor in (17), $\sqrt{bK}/g$, is determined experimentally as follows. With an arrangement as shown in Fig. 2, except that the movable coil is attached to a standard condenser instead of the secondary circuit, having a known current I' in the field coils Fc, a standard condenser is discharged through the movable coil of the dynamometer. The instantaneous torque acting on the movable coil during discharge is given by the equation

$$T = g I' i_2 = +g I' dq/dt \qquad (18)$$

in which q represents the quantity of electricity in the

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condenser at any instant. Multiplying equation (18) by dt and replacing T·dt by its value from equation (8) and integrating we get

$$K\int_{\omega=0}^{\omega=\omega_{max.}} d\omega = +gI'\int_{q=Q}^{q=0} dq. \qquad (19)$$

Substituting the values for the limits and solving for $\omega_{max.}$ we obtain

$$\omega_{max.} = gI'Q/K = gI'CV/K. \qquad (20)$$

By the same procedure as in deriving (16) we get

$$\omega_{max.} = \theta'\sqrt{b/K}. \qquad (21)$$

In this equation θ' is the deflection of the dynamometer. Eliminating $\omega_{max.}$ from (20) and (21) and solving, we obtain

$$\sqrt{b/K}/g = CVI'/\theta'K \qquad (22)$$

which, when substituted in equation (17), gives the working equation,

$$W = 2\pi_1 r_2 CVI'\theta/\pi_2\theta' = K_1\theta. \qquad (2)$$

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If it is desired to determine the maximum magnetic flux density, the circuits are arranged as shown in Fig. 2, in which the dynamometer is used as a ballistic galvanometer, a separate steady current I'' being maintained in the field coils Fc. By throwing over switch S, thereby reversing the magnetizing current, a deflection of the dynamometer is obtained which is proportional to the flux density B corresponding to the magnetizing current I. This, put in the form of an equation, gives

$$B = K_2 \theta'' \qquad (23)$$

where θ'' is the observed deflection and K_2 a constant depending on the dimensions and windings of the iron ring and the current I'' maintained in the field coils Fc. The different factors of K_2 substituted in (23), gives

$$B = 10^8 r_2'' C V I' \theta'' / 2\pi n_2'' I'' = K_2 \theta'' \qquad (24)$$

which is the working equation for B, to be derived. On reversing the switch S the torque on the moving coil is given by

$$T = g I'' l_2 = g I'' e_2 / r_2 = g I'' n_2 d\Phi / r_2 dt. \qquad (25)$$

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Multiplying by dt and replacing T·dt by K·dω, we obtain

$$K\int_{\omega=0}^{\omega=\omega\ max.} d\omega = g I'' n_2 / r_2 \int_{-\phi\ max.}^{+\phi\ max.} d\varphi \qquad (26)$$

whence,

$$\omega_{max.} = 2 g I'' n_2 \varphi_{max.} / K r_2 . \qquad (27)$$

In this case, the equation corresponding to (16) is

$$\omega_{max.} = \theta'' \sqrt{b/K} . \qquad (28)$$

After eliminating $\omega_{max.}$ from (27) and (28) and solving for $\varphi_{max.}$, we get

$$\varphi_{max.} = r_2'' \sqrt{b/K}\ \theta'' K / 2 I'' n_2 g . \qquad (29)$$

Substituting the value of $\sqrt{bK}/g$ from equation (22), replacing $\varphi_{max.}$ by its value, $aB_{max.}$ and solving for B, we get the equation

$$B = 10^8 r_2'' C V I' \theta'' / 2 a n_2'' I'' \theta' = K_2 \theta'' \qquad (24)$$

The factor 10^8 is introduced to make the units reduce to lines of force per cm^2.

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For calibrating the instrument a condenser of 2 microfarads capacity, charged to a difference of potential of 14 volts, was discharged through the movable coil while a current of 1 ampere was maintained in the field coils. The observed deflection, which was read by a telescope and scale at a distance of 1 meter from the mirror, amounted to 6.35 scale divisions. For calibration $W = CVI'/\theta'$. For the determination of the loss per cycle $W = 2n_1r_2CVI'\theta/n_2\theta' = K_1\theta$. With n_1 and n_2 equal to 466 and 40 turns respectively, together with the value of CVI'/θ', K_1 was found to be 18495×10^{-6}. When C is in microfarads, I' in amperes, and V in volts, W is expressed in joules loss per cycle. This loss W, measured by the dynamometer deflection, represents the total energy loss in the iron ring and test coil circuit. Since the eddy current losses in the test coil circuit vary inversely as the time required for the cycle, while the hysteresis loss is independent of the time, the eddy current loss can be reduced to practically zero by placing in the circuit a choke coil D, which causes the magnetizing current in C_1 to reverse very slowly when the switch S is reversed.

The ring used was made up of 49 sheets of ordinary commercial iron, with a mean thickness of .443 mm., having an inside diameter of 15.3 cm., and an outside diameter of

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22.3 cm.; which gives a cross-sectional area of 7.6 sq. in., a mean path of 59.19 cm., and a volume of 450 cu. cm.

The following results, which were taken by the dynamometer method, were obtained by taking four readings; two of which were taken by first throwing the switch S and then reversing the throw. The next two were taken in the opposite direction, thus eliminating the discrepancies which arise from the movable coil, due to the field being reversed and to the difference in the torque of the suspension fibre in the two directions.

For the calculation of the energy loss per half cycle the data was as follows:-

I in amperes	$B_{max.}$	θ dif.	Loss in Joules.
	For 40 turns on C_2.		
.20	3150	2.27	.042
.25	4800	5.40	.100
.30	6000	7.30	.135
.338	7350	9.80	.181
.40	8250	13.51	.250
.448	9700	14.98	.277
.60	11000	19.30	.357
.675	12150	22.70	.420

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I in amperes	$B_{max.}$	θ dif.	Loss in Joules
	For 18 turns on C_2.		
.90	12900	11.32	.465
.955	13800	12.80	.525
1.50	14800	14.72	.605
2.00	15600	17.00	.700
3.00	16400	20.40	.840
4.00	16800	23.40	.960

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In order to check the accuracy of the dynamometer, a series of tests, covering a wide range of induction, was made on the same ring by the ballistic galvanometer method. The galvanometer used was of the Rowland Wall type, having a period of 11 seconds and a resistance of 250 ohms.

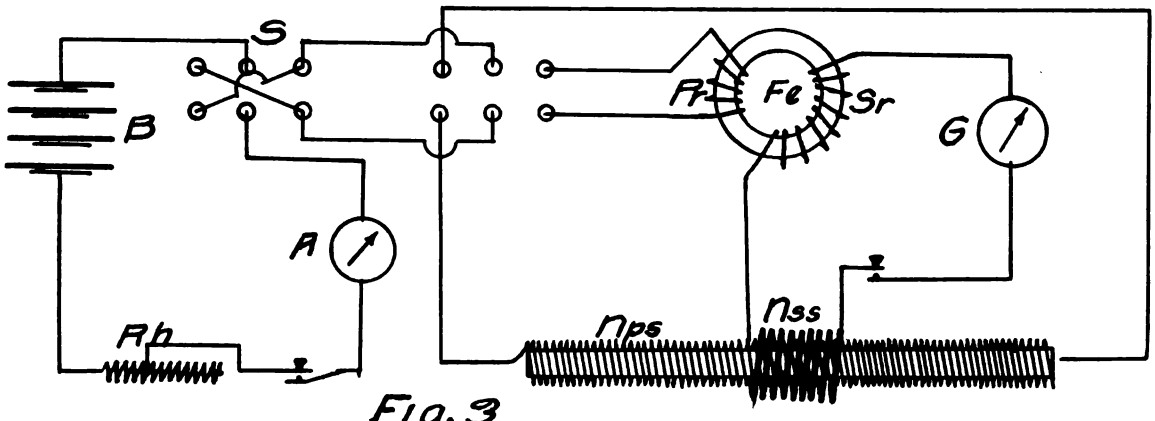

Fig. 3

It was calibrated by means of a standard solenoid. In making these tests the following modification of the original Rowland method, which is due to Taylor[2], was used. With the apparatus arranged as shown in Fig. 3, when the intensity of magnetization M, $(B-H/4\pi)$, is raised to the desired amount by Rh, the circuit is broken causing the magnetization to fall to retentivity and the deflection observed. The change of flux B, corresponding to the change in magnetization, is

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[2]Phys. Rev., Vol. XXIII, p. 95, 1906.

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proportional to the deflection, and to a constant K_3 depending on the windings of the ring, the current I, and the dimensions and windings of the solenoid. This, put in the form of an equation, gives

$$B=\left(\frac{4\pi \cdot n_{ss} \cdot n_{ps} \cdot A_s \cdot 10^8 \cdot R}{10^9 \cdot R \cdot l \cdot n_{sr} \cdot A_r}\right) I/d\, dr = K_3\, dr \qquad (30)$$

where n_{ss} = number of turns on the secondary of solenoid.

n_{ps} = number of turns on the primary of solenoid.

A_s = area of solenoid.

d_r = deflection on ring.

d_s = deflection on solenoid.

When the current is reversed 4π in the above equation becomes 8π because the flux is doubled. The field strength H is given by the equation

$$H = 4\pi n_{pr} I/10l = K_4 I . \qquad (31)$$

For the given set up of the instrument, n_{ps}/l was 5.16, n_{ss} 200, I/d_s .4, A_s 12.55 sq. cm., which gives for K_3 1712, and for K_4 9.88.

The damping coefficient which was calculated from the following data amounted to 9.45%. The observed deflections were: 5.6; -5.3; 5. ; -4.7; 4.3.

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$$\lambda = 1/4 \log_{10} 5.6/4.3 \times .4343 = .1193$$

Correct rdg. = observed $(1 + 1/2\lambda)$.

The following data for the hysteresis curves were calculated from retentivity B_r.

I in amp.	d.	d.corr.	H.	B.	M.
Curve (1).					
4.0	2.3	2.44	39.6	16350	1300
3.0	2.14	2.27	29.6	16070	1280
2.0	1.93	2.04	19.8	15670	1248
1.0	1.6	1.7	9.88	15080	1200
.5	1.2	1.27	4.95	14340	1142
- .5	12.5	13.4	-4.95	-6650	-530
-1.0	15.4	16.3	-9.88	-11550	-920
-2.0	16.9	17.9	-19.8	-14350	-1140
-3.0	17.5	18.5	-29.6	-15350	-1220
-4.0	18.0	19.1	-39.6	-16350	-1300

B_r was 12170. I was 969.

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I in amp.	d.	d.corr.	H.	B.	M.
Curve (2).					
1.5	1.67	1.77	14.8	14750	1175
1.2	1.5	1.59	11.8	14440	1150
.9	1.4	1.48	8.9	14260	1135
.6	1.19	1.26	6.94	13880	1107
.3	.8	.85	2.98	13170	1050
.1	.37	.39	.98	12390	987
- .3	8.8	9.2	- 2.98	- 1000	- 79
- .6	12.8	12.8	- 6.94	- 7150	- 570
- .9	15.1	16.0	- 8.9	-12650	-1007
-1.2	15.8	16.7	-11.8	-13850	-1102
-1.5	16.3	17.2	-14.8	-14850	-1175
		B_r = 11720.	I = 935.		
Curve (3).					
.9	1.32	1.4	8.90	12900	1025
.6	1.1	1.16	5.930	12500	997
.3	.75	.795	2.960	11860	945
.2	.6	.635	1.980	11590	923
.1	.32	.339	.988	11080	884
-.2	4.3	4.55	-1.980	5100	406
-.3	8.8	8.3	-2.960	- 1300	- 103
-.6	13.0	13.75	-5.930	-10700	- 853
-.9	14.2	15.1	-8.900	-12900	-1025
		B_r= 10500.	I = 837.		

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I in amp.	d.	d.corr.	H.	B.	M.
Curve (4).					
.4	.78	.825	3.96	8450	673
.3	.6	.635	2.97	8120	647
.2	.48	.51	1.98	7900	630
.1	.28	.297	.988	7550	602
-.15	2.53	2.68	-1.48	5850	466
-.2	4.28	4.55	-1.98	650	51.7
-.3	7.35	7.80	-2.96	-4900	-390
-.4	9.3	9.85	-3.96	-8450	-673

B_r = 7040. I = 560.

Curve (5)					
.2	.43	.445	1.98	3160	251
.15	.34	.36	1.48	2995	238
.1	.25	.265	.988	2835	225
.05	.15	.159	.495	2650	211
-.1	1.1	1.169	- .988	1160	92.5
-.15	2.2	2.33	-1.48	- 840	- 66.8
-.2	3.48	3.69	-1.98	-3160	-251

B_r = 2380. I = 189.5

When one unit of H is plotted to scale to equal one centimeter as abscissa, and when one unit of M, intensity of magnetization, is plotted to scale to equal one centi-

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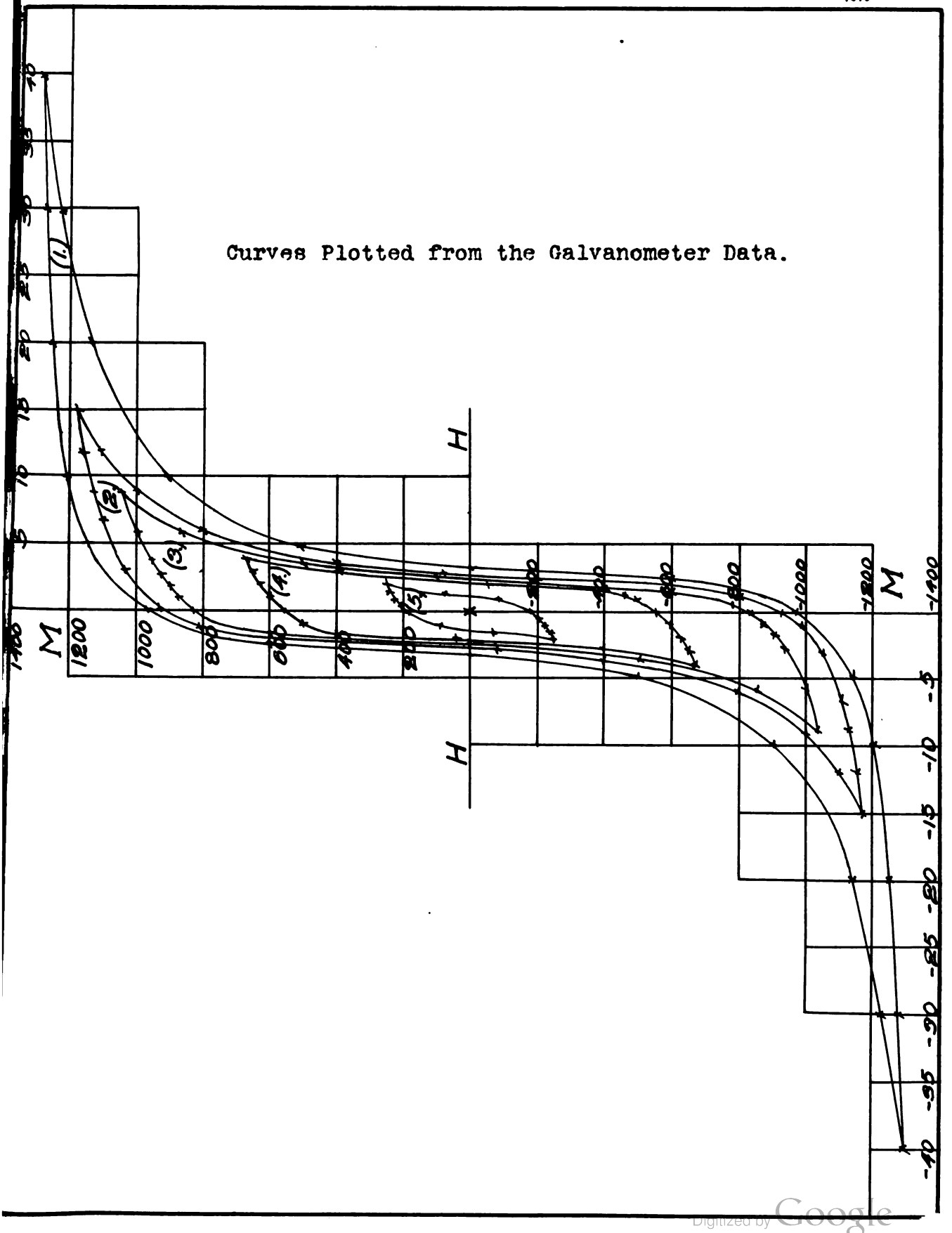
Curves Plotted from the Galvanometer Data.



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meter, the area of the curve is equal to the loss of energy in ergs per cycle, per cu. cm. of material. This, multiplied by volume of ring 450 cc. and divided by 10, gives the total loss in joules. The loss thus obtained for the curves 1,2,3,4 and 5, as shown in Fig. 4, was 1.084; .577; .464; .230; and .0397 respectively.

For a comparison of the results of the two different methods the losses were plotted as ordinates with their corresponding max. B as abscissae, which gives a curve showing the dissipation of energy per cycle as shown in Fig. 5.

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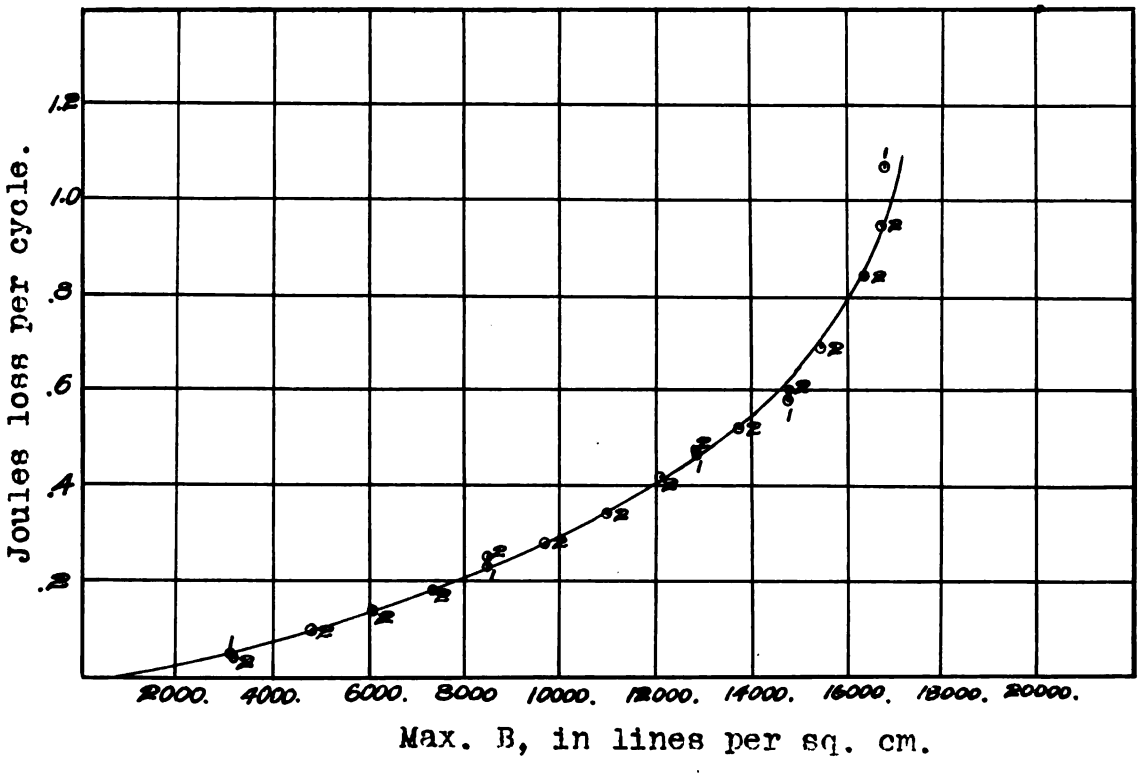
Fig. 5.



The above curve shows the energy loss per cycle. The points marked number 1 were taken by the galvanometer method and those marked number 2 were taken by the dynamometer method.

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The results as plotted in Fig. 5 show that the accuracy of the measurements obtained by the dynamometer method are on a par with those of the galvanometer method. The greatest portion of the measurements taken are within 2% of the curve drawn through the center of gravity of the points. The greatest advantage in the instrument is that it enables one to measure the losses for many different values of the magnetizing field within a very short time, after the instrument has once been set up and calibrated.

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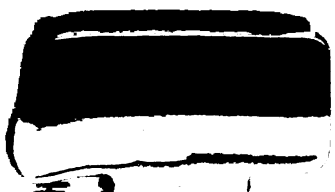

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